

Dimpled Ball Grid Array Process Development For Space Flight Applications

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ABSTRACT

With smaller and smaller Printed Wiring Board (PWB) form factors, such as CompactPCI[®], the need for smaller packages with high I/Os has grown significantly. Thus, the use of Ball Grid Array packages has become necessary for space flight applications. A Jet Propulsion Laboratory/NASA technology and system development program that services various spacecraft missions uses a 3U CompactPCI[®] form factor. The System Input/Output board requires a large amount of I/Os and has limited area, so the conventional packages, such as quad flat packs will not fit. A 472 Dimpled Ball Grid Array (D-BGA) package was chosen for this application. Since this type of package has not been used in past space flight environments, it was necessary to develop a process that would yield robust and reliable solder joints. The process, developing assembly, inspection and rework techniques, were verified by conducting environmental tests. The test article was a printed wiring assembly (PWA) consisting of four daisy chained D-BGA packages. Visual inspection of the outer solder joints and real time X-ray were used to verify solder quality. Three environmental tests were conducted: random vibration at 0.2 g²/Hz, pyro shock at 2000g for 50 ms, and thermal cycling from -55 °C to 100 °C for 200 cycles. The test article was electrically monitored for shorts and opens at or above 1 μs during all environmental tests. After testing, Scanning Electron Microscope (SEM) analysis was performed on various D-BGA cross sections to determine the quality of the package-to-board interface. Since the 472 D-BGA packages passed the above environmental tests within the specifications, the process was successfully developed for space flight electronics.

Key words: BGA, D-BGA, process, validation

INTRODUCTION

This paper summarizes the results of the process development for assembling 472 Dimpled Ball Grid Array (D-BGA) packages for space flight use. The test consisted of assembly, rework, and inspection techniques. Environmental tests such as random vibration, pyro shock, and thermal cycling were conducted to verify the process. The process for assembling BGAs has been developed industry wide for both aerospace and commercial applications, however the applications for space have been limited, due to the low volume manufacturing. This development effort was to qualify a process for space applications to withstand the requirements due to environmental exposure. The materials and processes must be more robust to meet the stringent requirements of space flight build.

ASSEMBLY AND TEST CONFIGURATION

A 472 Dimpled BGA package was chosen since its reliability margin was proven to be higher than standard BGA packages or Column Grid Arrays. (Data from the manufacturer is available). D-BGAs are similar to regular BGAs with a small column, or dimple, between the ball and the package, see Figure 1. It is the added dimple that increases the life cycle of the part by reducing the stresses caused by the different Coefficients of thermal expansion (CTEs) of the package and the PWB. The packages were internally daisy chained. The majority of the D-BGA packages had Sn60/Pb40 solder balls, with a small portion having Sn46/Pb46/Bi08 solder balls for comparison.

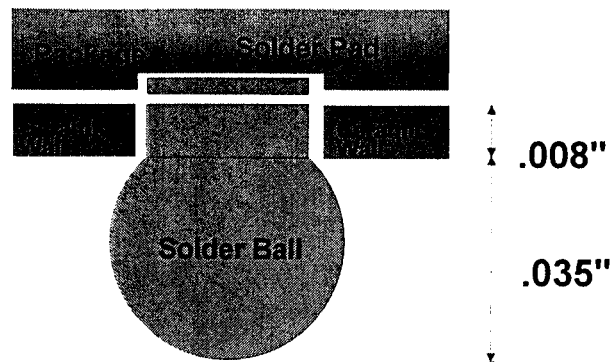


Figure 1. Solder joint on a Dimpled BGA

The board was designed using non-solder mask defined pads for the D-BGAs. Figure 2 shows the configuration of non solder mask defined pad. The PWB was 6 layers with simulated ground planes and was 0.080" thick. Two different board materials were used to see if their CTEs would effect the solder joint reliability. There were total of 7 polyimide (Polyimide-glass per IPC-4101/40) and 3 Aramid (Aramid polyimide per IPC-4101/53) PWA's. The boards had solder mask up to the solder pad and also on the vias. This solder mask design was based on previous design evaluations. The results obtained with both sets of boards are discussed in PWB assembly section. Figure 3 shows a PWB with insufficient solder mask and one with proper solder mask.

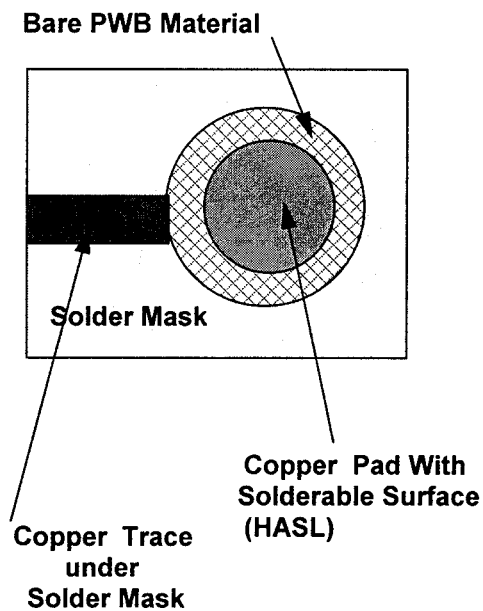


Figure 2. Non solder mask defined pad

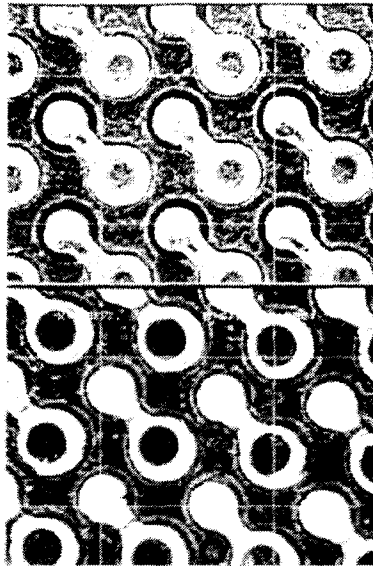


Figure 3. Solder mask, sufficient (top) and insufficient (bottom)

D-BGA Assembly Process

The assembly process was divided into the following distinct steps:

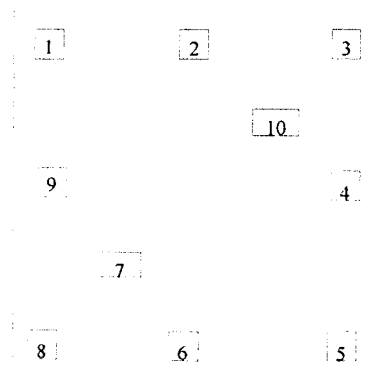
- Preassembly Prep and Inspection which included:
 - Coplanarity check
 - Solderability check (Board plating check)
 - Solder reflow profile development
 - Integri-test (opens and short test)
 - Cleaning, Baking and Storage of PWBs and D-BGAs
 - Inspection
- Screen Printing
- Solder paste Height Measurement
- Pick and Place components
- Vapor phase Reflow Soldering
- PWA cleaning
- Cleanliness verification
- Final Inspection

Preassembly Prep and Inspection

A coplanarity check was performed on all DBGAs using a very high power microscope prior to its assembly on PWB. A sample of the results is tabulated below (Table 1). During the coplanarity measurements, solder ball height (diameter) was measured with reference to the plane of the substrate. After testing numerous D-BGAs, the average variation in solder ball height was about 1.3 mils (0.0013 in.).

Table 1. D-BGA Coplanarity

ZONE	D-BGA ball diameter (in.)			
	S/N 001	S/N 002	S/N 003	S/N 004
1	0.0295	0.0322	0.0303	0.0297
2	0.0304	0.0323	0.0315	0.0297
3	0.0298	0.0308	0.0304	0.0298
4	0.0299	0.0319	0.0302	0.0302
5	0.0306	0.0313	0.0310	0.0299
6	0.0305	0.0325	0.0311	0.0298



7	0.0300	0.0322	0.0306	0.0293
8	0.0293	0.0321	0.0302	0.0298
9	0.0295	0.0336	0.0305	0.0301
10	0.0296	0.0319	0.0304	0.0296

A solderability testing instrument was used to qualify and quantify the type and amount of oxides on the surface of a PWB. The instrument works on the principle of Sequential Chemical Reduction Analysis.

Profile development was carried out using an instrument with a microprocessor based data logger and evaluator. The key factor was to measure temperature gradients underneath the D-BGA, since it is last to reach the desired temperature. Thermocouples were placed under the D-BGAs from the bottom side by drilling a hole in the center of the D-BGA portion of PWA. Then a thermal profile was generated. It was evident from the graph, Figure 4, that maximum preheat temperature reached was 110°C, which was lower than the targeted temperature of 130°C to 160°C. Also the dwell time above liquidus (183°C) was 140 seconds versus the desired dwell time of 80 to 100 seconds. The PWAs were run with four D-BGAs. After several attempts with different preheat temperatures and dwell times, the reflow profile was developed wherein the maximum preheat temperature of 133°C under the D-BGA was reached.

Integri-tester equipment, which tests the board from the net list data and detects opens and shorts on the PWB, was used to check the quality of the PWB.

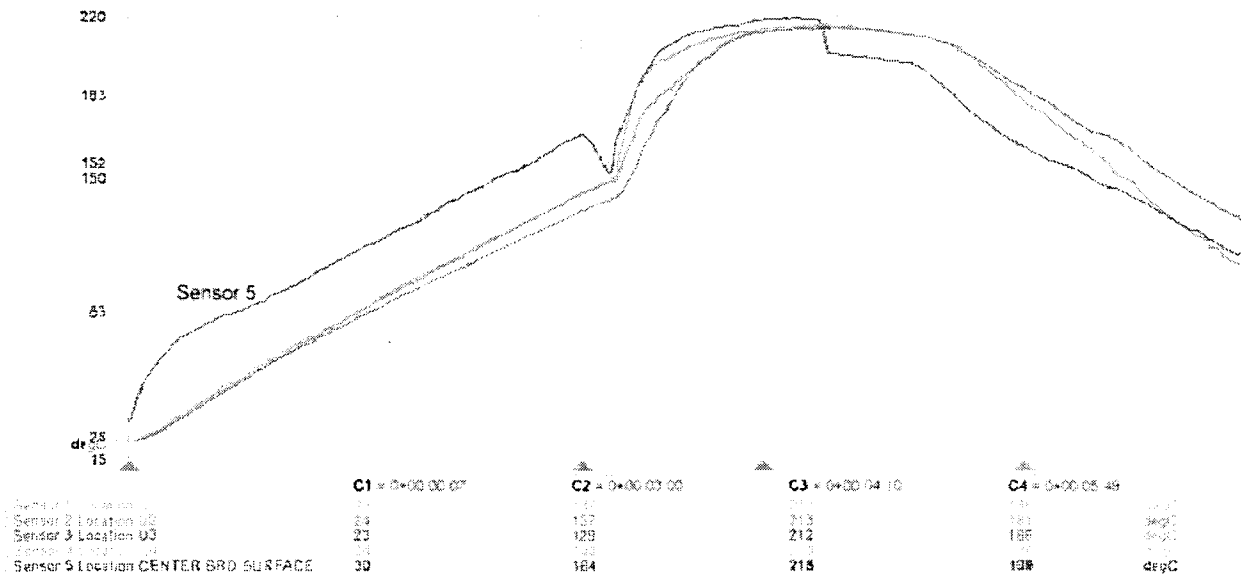


Figure 4. Reflow Profile

For high reliability space flight applications it is important that the PWB and components be cleaned thoroughly. The PWBs were cleaned as follows: cleaned in a batch cleaner using DI water with a saponifier, rinsed with DI water followed by isopropyl alcohol. The D-BGAs were cleaned with isopropyl alcohol manually. After cleaning the PWAs were baked in a vacuum oven at 100°C for minimum of 8 hours. When not in use, all boards & parts were stored in N₂ dry box to prevent oxidation.

All test boards and D-BGAs were visually inspected under microscope at 10X to 20X for defects such as damage to the board material or circuitry, proper solder mask application, discoloration or delamination of board material, missing or damaged pads, missing or damaged balls on D-BGA, damage to the D-BGA package, solder ball cracks, or any residue.

Screen Printing

A 7-mil thick laser cut stencil was used for solder paste deposition. Sn63/Pb37 solder paste with RMA type flux was used.

Solder Paste Height Measurement

Solder paste height was measured at various locations using a laser based 3-D measurement system. The paste was measured in 20 locations with an average height of 7.54 mils and a maximum delta of 1.1 mils.

Pick and Place of Components

The bottom side of the PWB was assembled using an automatic pick and place machine whereas the D-BGAs on the top side were placed with a computer controlled rework system using split vision.

Vapor phase reflow soldering

A vapor phase reflow system was used after developing the thermal profile above. The process consisted of preheating in a N₂ environment, reflowing at 215°C, and cooling down.

Cleaning and baking post assembly

The PWAs were cleaned as follows: Cleaned in a semi-aqueous batch cleaner using a Terpene solvent. Then cleaned in an aqueous batch cleaner using DI water with a soaponifier, rinsed with DI water followed by isopropyl alcohol, then tested in an ionograph for ionic residues. The PWAs were then baked in a vacuum oven at 70°C for 30 minutes.

Final Inspection

The height of each D-BGA package was measured with respect to the PWB surface to determine the coplanarity of the package after reflow, see Table 2. The outer solder balls were visually inspected using both a conventional microscope and also an ERSAscope optical inspection system, see Figure 5 and 6. Real time X-ray was also used to check for missing solder balls, shorts, voids, pad to ball alignment, and reflow problems. Figure 7 is an example of one of the X-rays.

Table 2. Post Reflow Coplanarity Data (in.)

ZONE	POLYIMID S/N 003		ARAMID S/N 004	
	BGA S/N 007	BGA S/N 008	BGA S/N 004	BGA S/N 010
1	0.1370	0.1348	0.1420	0.1428
2	0.1407	0.1389	0.1468	0.1502
3	0.1450	0.1422	0.1541	0.1572
4	0.1451	0.1408	0.1532	0.1600
5	0.1491	0.1439	0.1559	0.1605
6	0.1465	0.1399	0.1512	0.1553
7	0.1417	0.1357	0.1435	0.1491
8	0.1391	0.1335	0.1441	0.1451

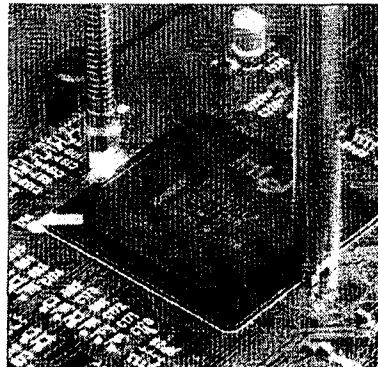


Figure 5. ERSAscope inspection system



Figure 6. Side view of D-BGA using ERSAscope

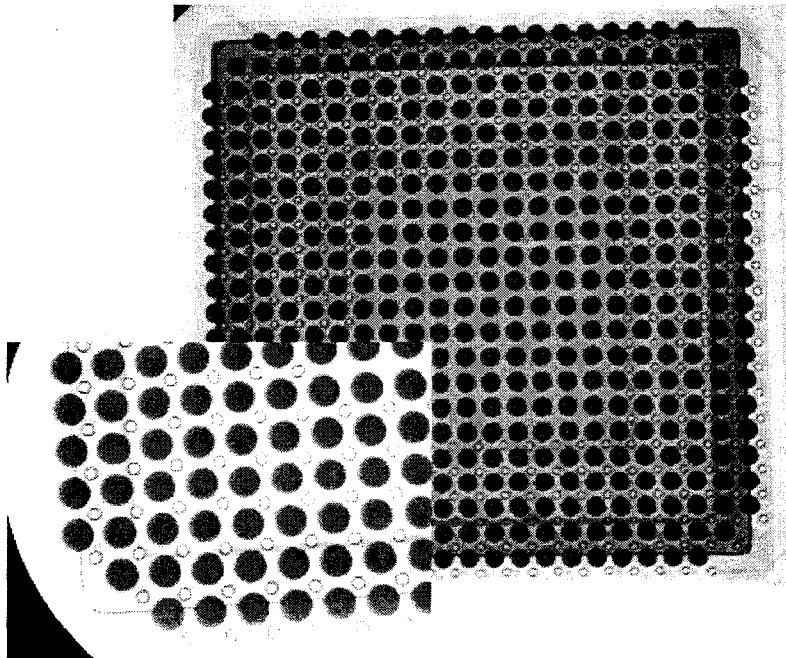


Figure 7. X-ray of D-BGA

D-BGA Removal

A process was developed to remove a D-BGA from a PWB using computer controlled rework equipment with split vision system. A D-BGA removal profile was generated using the same instrument as one used to generate the vapor phase profile. Nitrogen gas was used as a heating medium during the rework process development. The cycle was set in such a manner that the top and the bottom side were heated at a rate less than 1°C/sec. After several attempts, using different combinations of heat, % gas flow and duration of heat, the rework profile for the removal of a D-BGA was obtained. The maximum reflow temperature reached was 206°C.

Test Article

The test article (TA) was a printed wiring assembly (PWA) with two to four D-BGA packages, see Figure 8. The PWA was designed to represent a 3U CompactPCI® slice. See Table 3 for PWA test designation. The test PWA was designed such that when the D-BGA was attached, four daisy chains per package were formed. Part of PWB daisy chain is shown in Figure 9. Dummy parts were placed on the backside of the PWA to simulate a double-sided assembly. The D-BGAs were placed on the PWB in the approximate locations as flight. The thermal cycling PWAs had test connectors installed on the board for

electrical monitoring. The shock and vibration test boards had wires soldered to the board for electrical monitoring. This board also had heat sinks, Card-locs, CompactPCI® connectors, and a front panel.

An aluminum, six slot flight-like chassis was used for the shock and vibration tests. There were five PWAs installed in the chassis, two of which were D-BGA boards. The test axes and accelerometers are shown in Figure 10.

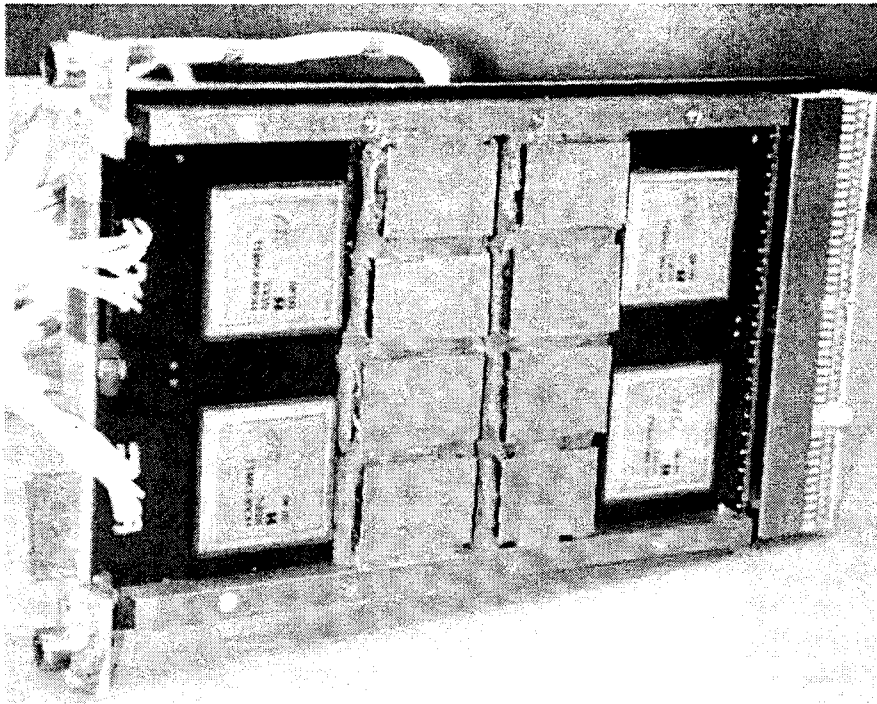


Figure 8. D-BGA Test Assembly

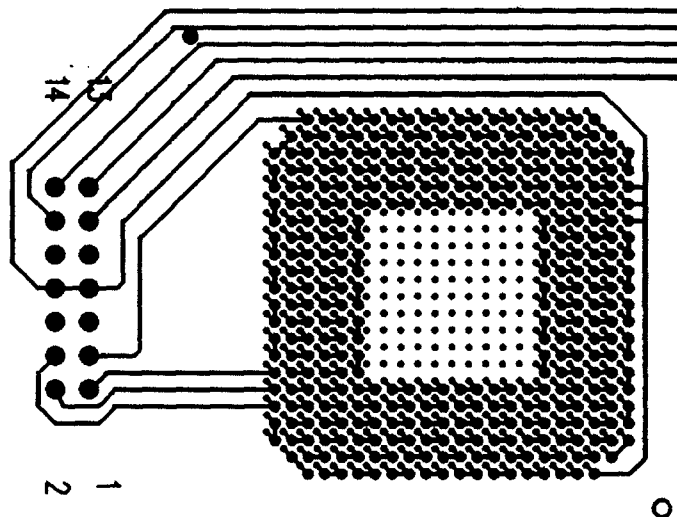


Figure 9. Art work on PWB

Table 3. SIO D-BGA Assembly Matrix

S/N	PWB Material	Test	Comments
1	Polyimide	Thermal Profile	
3	Polyimide	Thermal Cycle	Cross Sectioned @ 150 & 200 1 sec electrical monitoring
4	Aramid	Thermal Cycle	Cross Sectioned @ 200 1 sec electrical monitoring
5	Polyimide	Removed D-BGAs	Some cold solder joints.
6	Aramid	Shock & Vib	Some cold solder joints. 1 μ sec electrical monitoring
7	Polyimide	Thermal Cycle	Some solder columns. 1 μ sec electrical monitoring
8	Aramid	Final Thermal Profile	Used 1 new plus 3 dummy D-BGAs.
9	Polyimide	10 Thermal Cycles Shock and Vib	Ideal solder joints. 1 μ sec electrical monitoring

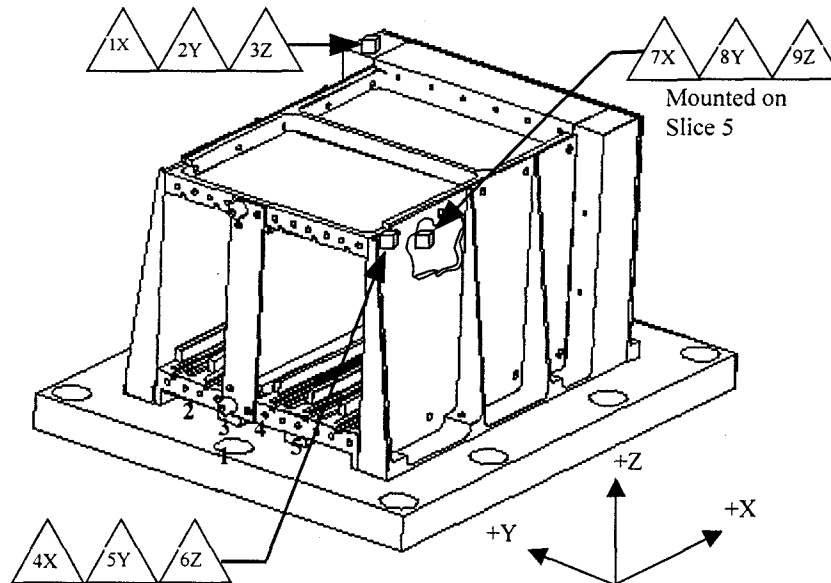


Figure 10. Vibration & Shock Test Chassis

ENVIRONMENTAL TESTS

Electrical continuity tests were performed with a Fluke meter to assure integrity of all soldered connections before and after each test. All environmental tests were electrically monitored continuously for shorts and opens above 1 μ s during testing.

Thermal Cycling was performed using the following profile, per NASA specification [1]:

- Temperature High End: 100°C \pm 2°C
- Temperature Low End: -55°C \pm 2°C
- Dwell at maximum temperature: 1/2 hour minimum
- Dwell at minimum temperature: 1/2 hour minimum
- Transition rate (high-to-low and low-to-high): \leq 5°C/minute

This standard NASA thermal profile was chosen since it is representative of a typical life cycle of a PWA through the assembly process, testing, launch, and a spacecraft mission with a large safety margin (a factor of 3 to 4). An equation derived by Dr. Ross [2], from the Coffin-Manson Law of metal fatigue, shows a relationship between the number of thermal cycles (N), or life cycles, and the delta in temperature (ΔT) as follows:

$$\frac{N1}{N2} = \left(\frac{\Delta T2}{\Delta T1} \right)^{2.6}$$

S/N 003 and 004 were thermal cycled to 200 cycles. The Polyimide (S/N 003) board had a D-BGA part cross sectioned at 150 cycles and one at 200 cycles. The Aramid board (S/N 004) was cross sectioned at 200 cycles. S/N 007 was thermal cycled for 300+ cycles, and will continue to be cycled until a failure occurs. S/N 009 was also thermal cycled for 10 cycles before going to the Shock and Vibration tests. S/N 010 will be thermal cycled to failure at a later date.

The random vibration test spectrum is defined in Table 4. The higher-level (severe) random vibration test spectrum is defined in Table 5. The test spectrum for the low level sinusoidal survey test is provided in Table 6. The low level sinusoidal survey test was performed to assess the structural integrity of the PWA and to gain insight into the modal characteristics of the assembly.

Table 4. Initial Random Vibration Test Spectrum

Frequency Range (Hz)	Qualification Test Level
20	0.032 g ² /Hz
20-50	+9 dB/octave
50-250	0.20 g ² /Hz
250-350	-6 dB/octave
350-1000	0.10 g ² /Hz
1000-2000	- 12 dB/octave
2000	0.0063 g ² /Hz
Overall	12.3 g _{rms}
Test duration: Three minutes per axis	

Table 5. Severe Random Vibration Test Spectrum

Frequency Range (Hz)	Protoflight Test Level
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20	0.032 g ² /Hz
20-70	+6 dB/octave
70-300	0.40 g ² /Hz
300-400	-6 dB/octave
400-800	0.20 g ² /Hz
800-2000	- 9 dB/octave
2000	0.0129 g ² /Hz
Overall	16.7 g _{rms}
Test duration: Three minutes per axis	

Table 6. Sinusoidal Survey Test Spectrum

Frequency Band (Hz)	Test Level
5 – 2000	0.25 g 0-to-peak

Sweep Rate = 2 octaves per minute; One upsweep per axis

The PWAs were subjected to three pyroshock pulses in each axis, to simulate launch conditions. The shock waveform needed to satisfy both of the following criterion: A) be oscillatory in nature, and B) decay to less than 10% of its peak value within 50 milliseconds (Figure 11).

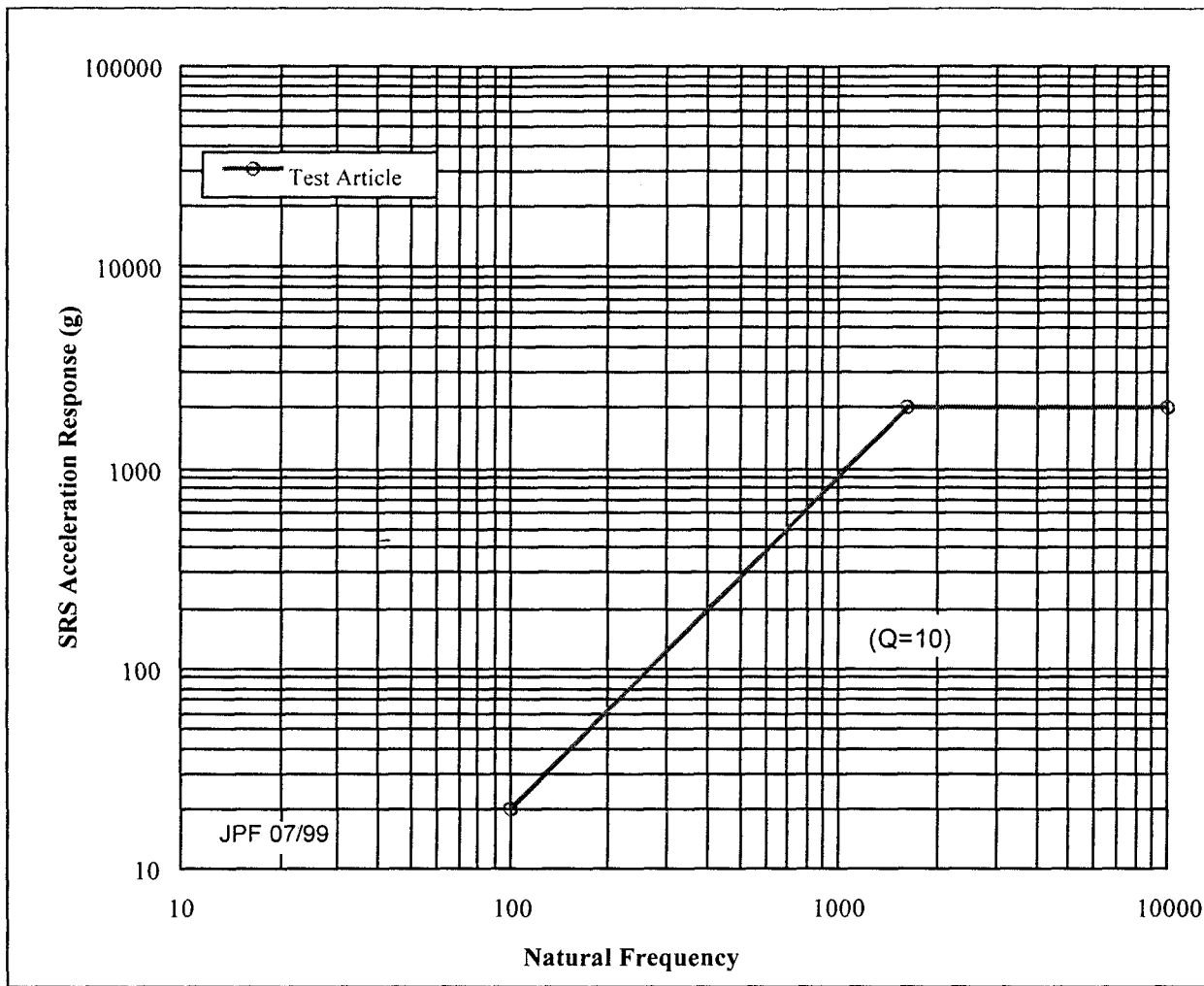


Figure 11. Pyroshock Design and Test Requirements for TA

To minimize over testing of the assembly, manual notching was imposed on the system at the natural resonance of the chassis during the Y axis and Z axis vibration test. The justification for this manual notch is based on an estimate of how the unit would respond when mounted to a flight-like support panel. If force limiting techniques were used, it is estimated that at least a 12 dB notch would have been observed. To that end, a manual notch was imposed at the natural frequency of the unit (544 Hz in Y; 1000 Hz in Z) for high level vibration runs. Without the manual notch, the electronics boards would have seen over 297 G's of load in the Z axis test and 181 G's in the Y axis test, which is too high for an assembly of this size.

ELECTRICAL MONITORING SYSTEM

Voltage is read across a sense resistor (97.5 ohms) by a differential measurement of two buffer amplifiers, see Figure 12 for schematic. This differential voltage is used to drive the photo-diode of the opto-coupler, which converts the analog measurement to a digital signal. When the differential voltage drops below 2.4 volts the diode gets voltage/current starved and the output from the opto-coupler transitions to a digital high (5 volts), indicating that the daisy chain circuit has gone to a high impedance state. The value of the daisy chain impedance at which the circuit transitions to open can be found in Table 7 below. When the resistance value of the daisy chain is below the chosen value found in Table 7 the opto-coupler output is LOW or 0 volts. The state (HIGH or LOW) of the daisy chain is captured by the RS Flip-Flop circuitry made up of two NOR gates. Once the opto-coupler output transitions from HIGH to LOW the Flip-Flop circuit captures the transition. This "memory" allows the data acquisition computer to leisurely read the outputs from all data channels. Once the computer has finished reading the data channels, supplying a +5 Volt pulse to the RESET line will reset the system. The nominal input of the RESET line must be LOW to ensure proper operation. At start-up the RESET line must also experience this +5 Volt pulse in order to bring the Flip-Flop into a known state. Acquisition times, daisy chain resistance's and Daisy chain voltage plus (+) V_{R98} set points can be found in Table 7 below. As can be seen in Table 7, different intermittent time resolutions

from 1 microsecond to 4.1 microseconds can be programmed into the system by varying the input voltage (Voltage across daisy chain and R). For proper operation the Daisy Chain must be put in series with resistor R.

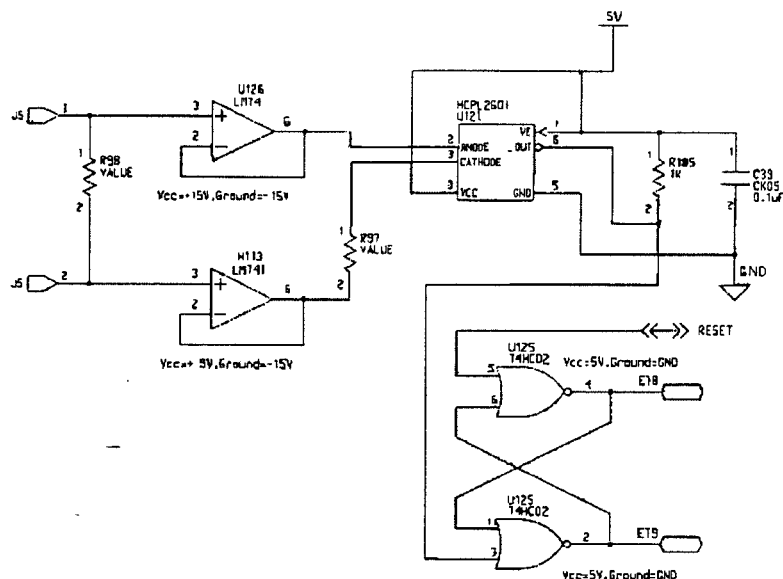


Figure 12. Monitoring System Schematic

Table 7. Experimental results of Intermittent Detection Circuit.

Collapse Voltage		2.4 V
Voltage	Trip Time (μ s)	Trip Res (ohms)
3	1	27
3.5	1.8	48
4	2.6	71
4.5	3.3	90
5	4.1	112

ENVIRONMENTAL TEST RESULTS

A summary of the results is shown in Table 8. The D-BGAs passed the thermal cycling tests with intermittents.

Table 8. Results Summary

S/N	PWB Mar'l	Test	Comments
1	P	Thermal Profile	Successful
3	P	Thermal Cycle 1 sec electrical monitoring	No intermittents. Cross Sectioned @ 150 & 200 No solder degradation. Slight cracks at solder mask.
4	A	Thermal Cycle 1 sec electrical monitoring	No intermittents. Cross Sectioned @ 200 No solder degradation. Slight cracks at solder mask.
5	P	Removed D-BGAs	Some cold solder joints. Used for rework test.
6	A	Shock & Vib 1 μ sec electrical monitoring	Some cold joints. One intermittent during sever vib.
7	P	Thermal Cycle 1 μ sec electrical monitoring	Some solder columns. No intermittents. At 450+ thermal cycles to date.
8	A	New Thermal Profile	Used 1 new plus 3 dummy DBGAs
9	P	10 Thermal Cycles Shock and Vib 1 μ sec electrical monitoring	Ideal solder joints. Intermittent during vib due to mass mock-up impact. Cross sectioned

S/N 008 was used as a thermal profile board and was also used as a control sample for cross sections. Figure 13 shows how the samples were cut from two sections. Figures 14 and 15 show typical cross sections of the control sample. These cross sections indicated that there is a small amount of separation between the dimple and the package.

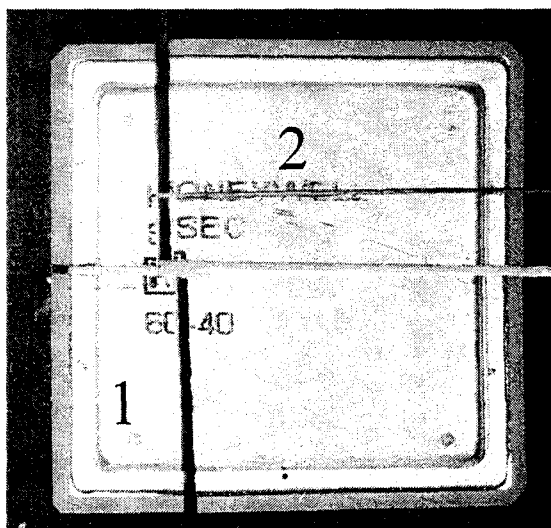


Figure 13. D-BGA Cut into Pieces #1 and #2

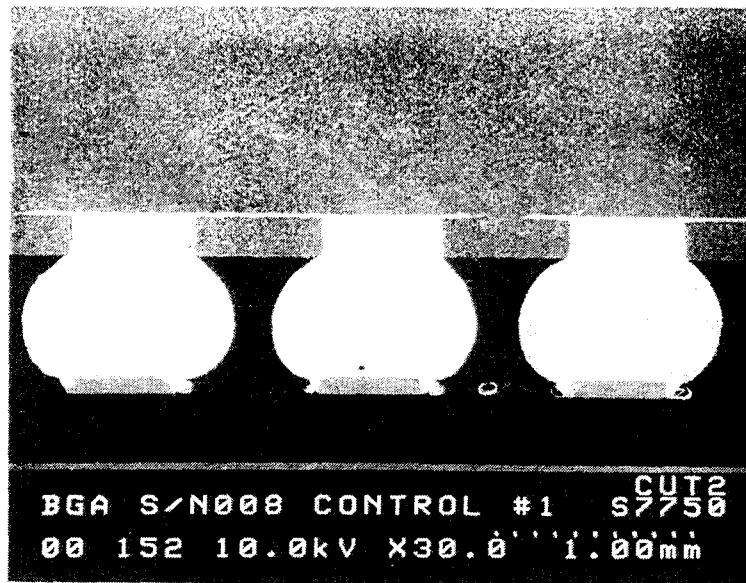


Figure 14. D-BGA Cross section, Control Piece #1

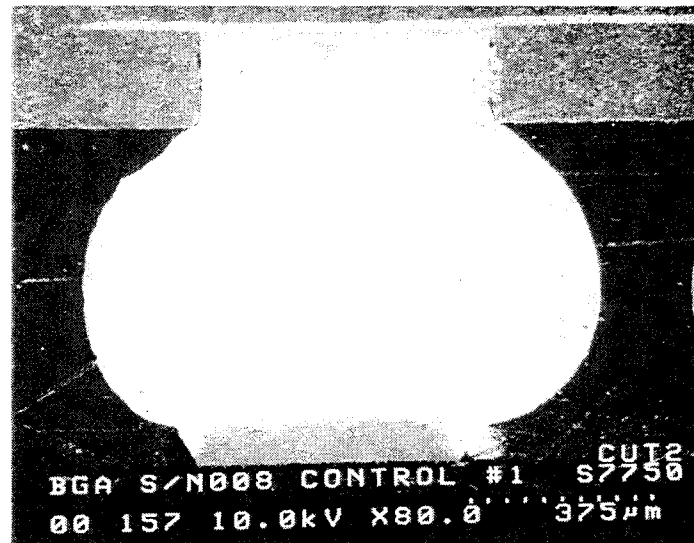


Figure 15. D-BGA Cross section, Control Piece #1 X80

Thermal Cycling

The test results through thermal cycling were positive since no opens or intermittents were observed. The cross section data exhibited a similar separation between the dimple and the package that was observed on the control sample. This separation is an inherited problem and was not due to thermal cycling. The separation may have increased slightly during thermal cycling, but not significantly enough to cause a failure. Cross sections were taken on one sample from S/N 003 at 150 thermal cycles. Figures 16 through 18 show an example of the separation between the dimple and the package. The cross section data also indicates some signs of cracking or separation at the point where the solder ball and the solder mask meet at the PWB. Figures 19 and 20 indicate an additional weak point; where the solder ball meets the solder mask. This crack disappears as the cross sections moves to the center of the ball. This will be discussed again further in the paper.

Cross sections were taken on one sample from S/N 003 (Polyimide) and S/N 004 (Aramid) at 200 thermal cycles. Figure 21 is a typical cross section after 200 thermal cycles.

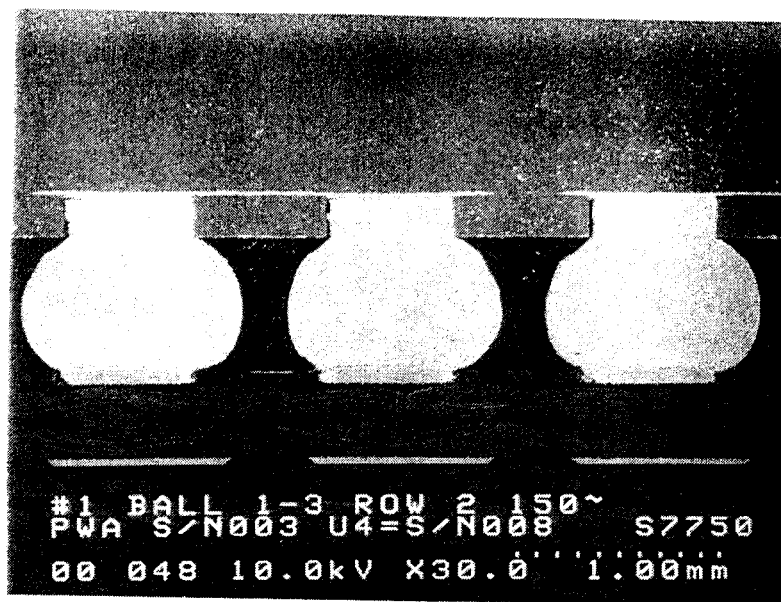


Figure 16. D-BGA Cross Section, 150 thermal cycles

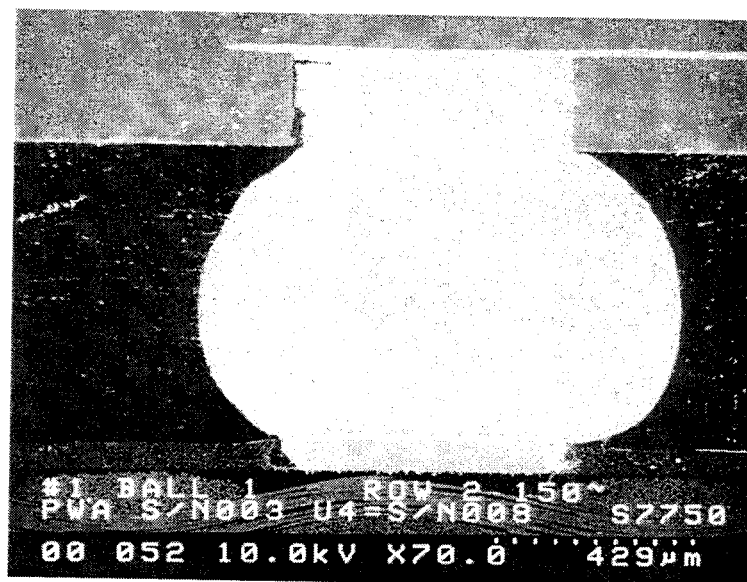


Figure 17. D-BGA Cross Section, 150 thermal cycles, X70



Figure 18. D-BGA Cross Section, 150 thermal cycles, X300

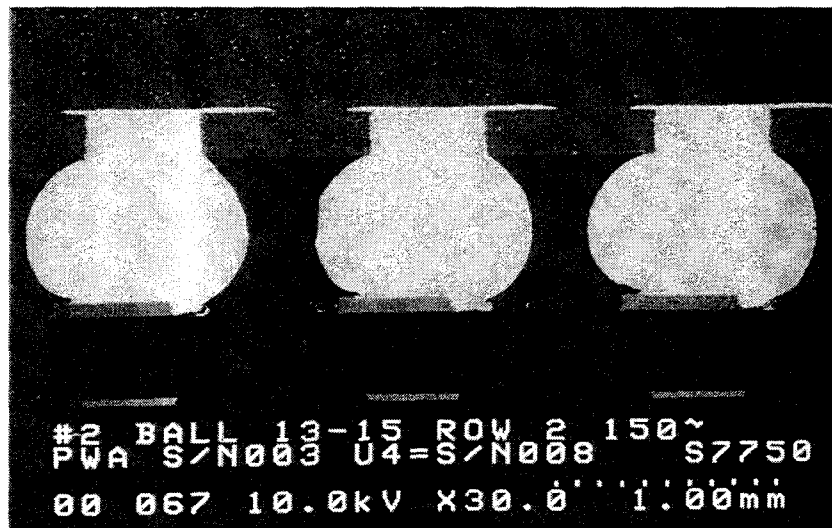


Figure 19. D-BGA Cross Section, Solder mask effect

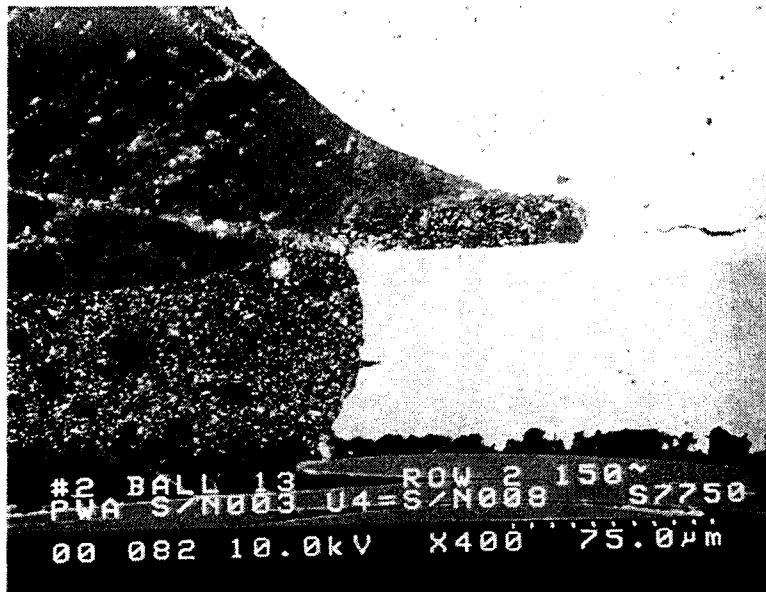


Figure 20. D-BGA Cross Section, Solder mask effect, X400

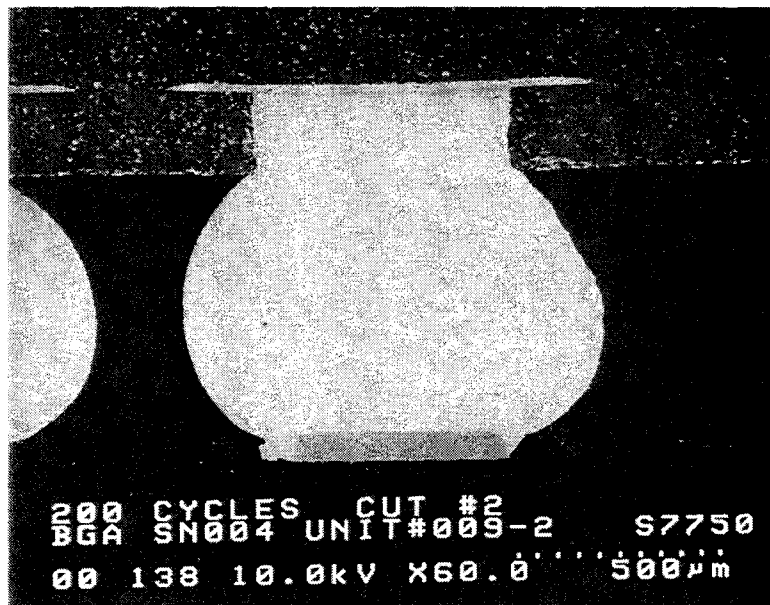


Figure 21. D-BGA Cross Section, 200 thermal cycles, Typical

The shock testing was completed successfully. The vibration test $0.2g^2/Hz$ run on the Z and X axes was run with no intermittents. One intermittent occurred during the $0.2g^2/Hz$ level in the Y-axis when a mass mock up piece fell off and hit one of the D-BGAs on S/N 009. The assembly was then tested at the $0.4g^2/Hz$ level in all three axis. The severe ($0.4g^2/Hz$) vibration caused one intermittent in the other D-BGA test board that had non ideal, or cold, solder joints. No other opens or intermittents occurred during testing.

After the test both D-BGA boards were visually inspected and electrically checked. The outer solder balls were visually inspected and appeared the same as prior to testing. The boards were also X-rayed, and showed no anomalies.

The cross section of the crack caused by the mass impact is shown in Figure 22. There were no signs of solder degradation, which would be evidence of a fatigued solder joint from the vibration test. Cross sections were also conducted on two other parts on S/N 009. Figure 23 shows a typical cross section. The cross sections revealed minor voiding at 500X that were likely caused by oxidation on the PWB pads during the fabrication process, see Figure 24. One part showed slight cracks at the ball to pad interface in a few locations near the corners, while another part had no cracks.



Figure 22. Cross Section of D-BGA A3, Cut 2

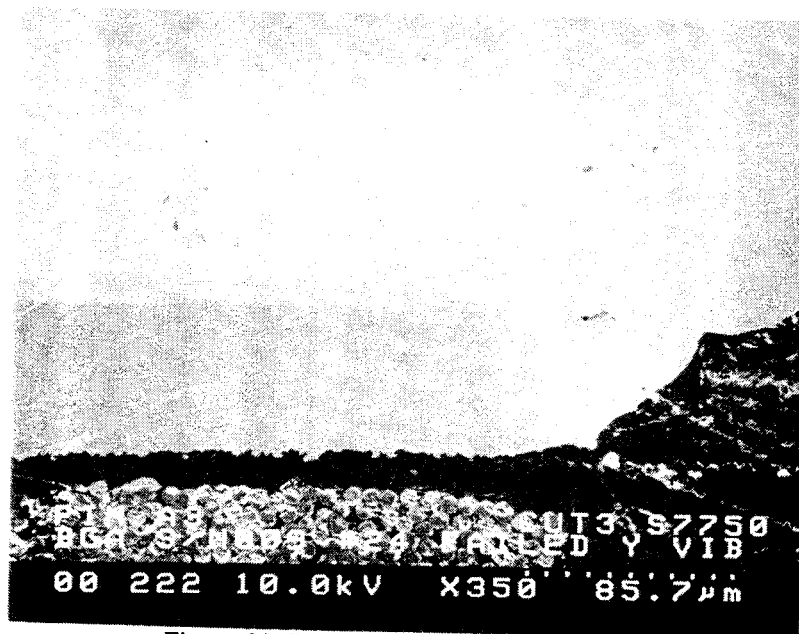


Figure 23. Typical Cross Section of D-BGA



Figure 24. Typical Cross Section, D-BGA, S/N 009-21

CONCLUSIONS

Knowing the cause of the intermittent channel during the vibration tests, it is concluded that the process used to attach D-BGA packages, had good solder joints, and can be used successfully for space flight applications. The intermittent that occurred during the vibration test, on S/N 009, was caused by the mass mock up falling off and the resulting mechanical damage to the solder joint. The cross section data shows no signs of solder joint fatigue. The D-BGA solder joints would not have failed until the cracks were induced by the mock-up piece. The D-BGA packages with good solder joints exhibited positive results through shock, vibration and thermal cycling requirements, up to 200 cycles, with no intermittents.

A standard D-BGA part with Sn63/Pb37 solder, using JPL's SMT assembly process, survived the thermal and mechanical environmental requirements. The cross section data showed no signs of solder joint fatigue. With the process used for military requirements in addition to those for flight applications, the results were successful. Based on the results of the environmental tests, the process for assembling 472 Dimpled Ball Grid Array (D-BGA) packages is now validated for space flight.

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